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Kinetic effects of thermal ions on the nonlinear evolution of energetic particle driven Alfvén eigenmodes

高エネルギー粒子駆動アルフベン固有モードの非線形発展における熱イオンの運動論的効果

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Particle-in-cell simulation is applied to thermal ions in addition to energetic particles in MEGA code, which is a hybrid simulation code for energetic particles interacting with an MHD fluid. This enables to investigate thermal ion kinetic effects on the nonlinear evolution of Alfvén eigenmodes destabilized by energetic particles. The simulation model and preliminary results are presented.

1. Introduction

The nonlinear evolution of a toroidal Alfvén eigenmode (TAE) was investigated using MEGA code [1], which is a hybrid simulation code for energetic particles interacting with an MHD fluid. It was found in the hybrid simulation that the zonal flow and the geodesic acoustic mode (GAM) are generated through the nonlinear coupling in MHD equations, and they reduce the saturation amplitude of the TAE [2, 3]. In the MEGA code, the bulk plasma is described by MHD equations, and no kinetic effect of the bulk plasma is taken into account. In this paper, we extend the MEGA code applying the particle-in-cell (PIC) simulation method to thermal ions in addition to energetic ions. It is well known that GAM is affected by the thermal ion Landau damping. Then, thermal ions should be treated kinetically to understand the zonal flow and GAM generation in the nonlinear evolution of TAEs. It is also expected that the kinetic damping of GAM affects the saturation level of TAE mode. Since zonal flows stabilize micro turbulence, this is an important issue to explore the self-organizing nature of burning plasmas where Alfvén eigenmodes may be destabilized by energetic alpha particles.

2. Simulation model

We apply PIC to thermal ions. Mass density and parallel velocity in the MHD equations are given by computational particles of thermal ions in this extended model. PIC gives also thermal ion pressure. We assume electron density equals to thermal ion density, and neglect electron temperature evolution. We solve the induction equation and the evolution of MHD perpendicular velocity that gives electric field through Ohm's law.

$$\frac{\partial}{\partial t}\left(\rho \mathrm{v}_k\right) = -\nabla(\rho \mathbf{v}\mathrm{v}_k) - \nabla p_e + (\mathbf{j} - \mathbf{j}'_i - \mathbf{j}'_h)\times\mathbf{B}$$

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla\times\mathbf{E}$$

$$\mathbf{E} = -\mathbf{v}\times\mathbf{B} + \frac{\nabla p_e}{(-e)n_e} + \eta(\mathbf{j} - \mathbf{j}_{\mathrm{eq}})$$

$$\mathbf{j} = \frac{1}{\mu_0}\nabla\times\mathbf{B}$$

$$n_e = (\rho / m_i)Z_i$$

$$p_e = n_e T_{e0}$$

$$\text{PIC: } \rho,\ \mathrm{v}_{\parallel},\ \mathbf{j}'_i(p_{i\parallel}, p_{i\perp}),\ \mathbf{j}'_h(p_{h\parallel}, p_{h\perp})$$

Here, v_k represents each component (k=R, φ, z) of MHD velocity $\mathbf{v}$ in cylindrical coordinates. The parallel component of v_k is replaced by $\mathrm{v}_{\parallel}$ that is given by thermal ion PIC. The thermal ion and energetic particle current $\mathbf{j}'_i$, $\mathbf{j}'_h$ consist of grad-B, curvature, and magnetization current. They are calculated using parallel and perpendicular pressure given by PIC. Electron pressure gradient is taken into account in Ohm's law. It should be noted that viscosity and density diffusivity are not employed in this model.

3. Results

The time evolution of a TAE with toroidal mode number $n=4$ is investigated using the standard MEGA and the extended MEGA with kinetic thermal ions. The TAE mode is the same as that examined in Ref. 2. Figure 1 compares the nonlinear evolution of the TAE between the extended MEGA simulation and the standard MEGA simulation. We see the evolutions are quite close to each other. The growth rate of the TAE is lower with kinetic thermal ions than with the MHD fluid model. This indicates that kinetic thermal ions stabilize the TAE. This stabilization exceeds the dissipation induced by viscosity that is not included the kinetic thermal ion model but included in the standard MEGA code. Figure 2 compares the zonal flow evolution in the two runs. The evolutions look similar to each other. The saturation amplitude of both the TAE and zonal flow is higher with kinetic thermal ions than with the MHD fluid model.

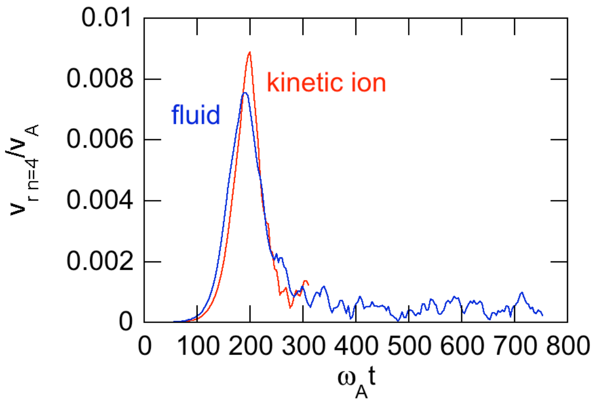

Fig.1. Comparison of radial velocity evolution of TAE between the standard MEGA (fluid) and the extended MEGA (kinetic ion).

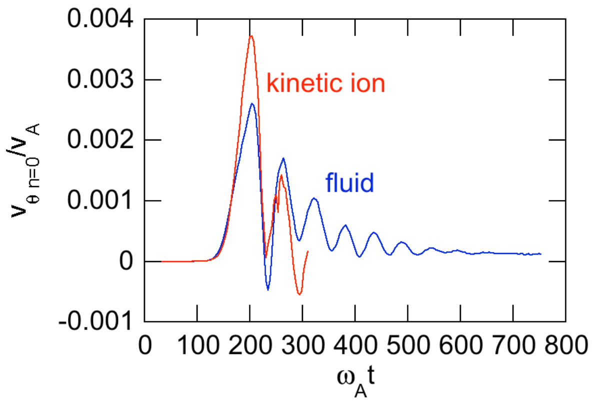

Fig.2. Comparison of zonal flow evolution between the standard MEGA (fluid) and the extended MEGA (kinetic ion).

4. Summary and discussion

We have extended the MEGA code applying the PIC simulation to thermal ions in addition to energetic particles. We have successfully simulated the evolution of a TAE and the result is quite close to that with the fluid MHD model. We need analyze energy transfer between thermal ions and the TAE to clarify whether the thermal ion Landau damping takes place or not. It would be interesting and important to investigate many cases to explore kinetic effects of thermal ions on the nonlinear evolution of Alfvén eigenmodes.

References

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